Advanced Wastewater Treatment Design for West Omdurman, Khartoum State, Sudan

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Abstract: ***In Khartoum State less than 5% of the generated wastewater receives adequate treatment before discharge, while more than 95% is discharged directly or indirectly to surface water and aquifers. In West Omdurman, on-site systems such as septic tanks, cesspits and soakaways are widely used and are a major source of microbiological and chemical contamination of the Nubian and Quaternary aquifers. This paper presents the conceptual design and expected performance of a centralized advanced wastewater treatment plant (WWTP) for West Omdurman, based on the hydrogeological and contamination inventory developed in the PhD study and on standard design criteria. The plant is sized for a design population of 450,000 inhabitants and an average wastewater flow of 60,000 m3/d. The proposed process line comprises bar screening, grit removal, primary clarification, biological treatment using conventional activated sludge with nitrification and denitrification, secondary clarification, rapid sand filtration and ultraviolet (UV) disinfection. Sludge is thickened, stabilized and dewatered prior to land application or controlled disposal. Design calculations give an aeration volume of 20,000 m3 (four basins of 5,000 m3 each), two primary clarifiers of 36 m diameter, four secondary clarifiers of 28 m diameter, a total rapid sand filter area of about 480 m2 and a disinfection contact tank of 1,800 m3. For typical medium-strength municipal wastewater (BOD5 ≈ 250 mg/L, COD ≈ 500 mg/L, TSS ≈ 250 mg/L, TN ≈ 40 mg/L, TP ≈ 8 mg/L), the system is expected to achieve effluent concentrations of BOD5 < 20 mg/L, TSS < 20 mg/L, TN 10–15 mg/L and TP 2–3 mg/L, with faecal coliforms < 200 CFU/100 mL after UV disinfection. These values satisfy international guidelines for the reuse of treated wastewater in restricted and many unrestricted irrigation applications and are sufficient to protect the stressed groundwater resources in West Omdurman. The paper also discusses the relative environmental performance of sand filtration, membrane bioreactors (MBR) and ozonation based on life-cycle assessment results from the thesis, highlighting that sand filtration combined with UV disinfection offers a favourable balance between energy use and prevented ecotoxic impacts.***

Keywords: wastewater reuse, groundwater protection, Nubian aquifer, West Omdurman, advanced treatment

1. Introduction

1.1 Background

Groundwater forms a strategic water resource for domestic supply, irrigation and industry in Khartoum State. More than half of the drinking water demand is supplied from groundwater, and in some localities it is the only realistic source for dispersed rural and peri-urban communities. At the same time, uncontrolled urbanization, industrial activities and expansion of irrigated agriculture along the Nile and in West Omdurman have increased the pressures on water quality.

In the absence of a comprehensive sewerage system, most households and many institutions rely on on-site sanitation and direct disposal of wastewater into the subsurface. The soils of Khartoum State are generally not capable of providing safe natural attenuation of these discharges, so effluents from septic tanks and pit latrines often reach shallow aquifers. The contamination inventory carried out in West Omdurman documented elevated concentrations of nitrate, ammonia, phosphate, faecal bacteria and other indicators in the Nubian and Quaternary aquifers, especially where shallow wells are located in densely populated or intensively cultivated areas.
Khartoum State currently has only two centralized wastewater treatment plants—the overloaded stabilization pond system at Soba and the conventional activated sludge/sequencing batch reactor plant in Khartoum North—both of which show performance and operational problems. Decentralized membrane bioreactor units and other advanced technologies have been introduced only at small scale.

There is therefore a clear need to design an appropriate, robust and sustainable wastewater treatment system for West Omdurman that can protect groundwater and surface water, enable safe reuse of treated effluent for irrigation, and gradually replace unsafe on-site sanitation. Building on the advanced treatment technology review and environmental assessment in the PhD thesis, this paper develops a complete process design and evaluates the expected performance of an advanced WWTP for the area.

1.2 Statement of problem

Khartoum State lies at the confluence of the White and Blue Nile. Seasonal variations in river discharge, intensive groundwater abstraction and uncontrolled wastewater disposal have combined to degrade both surface water and aquifers. In West Omdurman, domestic sewage is typically discharged through pits and septic tanks into highly permeable sediments. The soils do not meet the conditions required to act as natural barriers, which leads to rapid percolation of effluents into groundwater, carrying faecal coliforms, nutrients and other pollutants.

The contamination inventory demonstrated that many wells used for public supply and irrigation show elevated concentrations of nitrate, ammonia and other contamination indicators associated with sewage and agricultural return flows. Microbiological analyses detected faecal coliforms and streptococci in wells used for drinking water, confirming direct sanitary risks. Large-scale agricultural projects in West Omdurman abstract water from deeper aquifers, while shallow aquifers are locally depleted or polluted.

Existing wastewater treatment facilities in Khartoum State are insufficient in capacity and not located to address the specific sanitation challenges of West Omdurman. Without intervention, continued use of on-site sanitation will further deteriorate groundwater quality and increase treatment costs for drinking water, while the opportunity to reuse treated wastewater in agriculture remains largely unexploited. An appropriately designed centralized WWTP is therefore a key element of an integrated water resources management strategy for West Omdurman.

1.3 Objectives

The overall objective of this study is to develop and evaluate an advanced wastewater treatment concept for West Omdurman that protects groundwater resources and provides effluent suitable for reuse.

The specific objectives are to:
- Propose a technically sound and environmentally sustainable process configuration for an advanced WWTP serving West Omdurman, based on the hydrogeological and contamination assessment from the PhD thesis.
- Develop conceptual design calculations for all major treatment units, including flows, hydraulic loads and main dimensions.
- Estimate the expected effluent quality and removal efficiencies for organic matter, suspended solids, nutrients and microbiological indicators, with particular reference to groundwater protection and agricultural reuse.
- Compare, at a conceptual level, the environmental implications of different advanced treatment options (sand filtration, membrane bioreactors, ozonation) drawing on life-cycle assessment results, and justify the selected configuration.

2. Materials and Methods

2.1 Study Area and Location Map

The study area is located west of Omdurman and includes Omdurman locality and Al-Reef Al-Ganobei. It extends between latitudes 15° 47′ 3.62″ N and 15° 29′ 59.26″ N and longitudes 32° 15′ 31.33″ E and 32° 29′ 8.15″ E, covering about 720 km2. Land use is dominated by rapidly expanding residential zones, well fields for public water supply, and large irrigated farms using centre-pivot systems. Hydro geologically, the area is underlain by Quaternary alluvial sediments and the Upper Nubian Sandstone aquifer. The Nubian aquifer consists mainly of sandstones with interbedded mudstone and siltstone and is highly productive, but also vulnerable where overlain by permeable Quaternary sediments and numerous on-site sanitation systems.

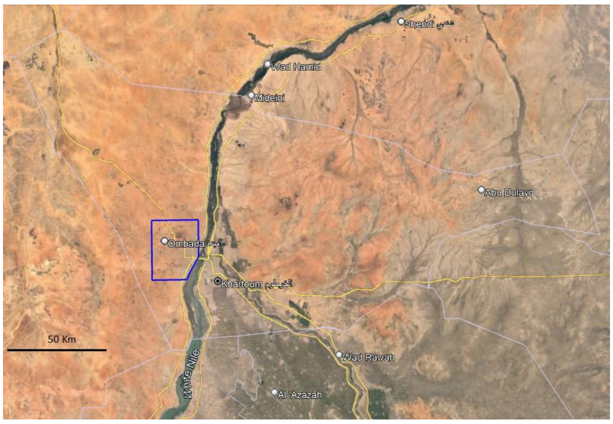

Figure 2.1: Location map of the West Omdurman study area.

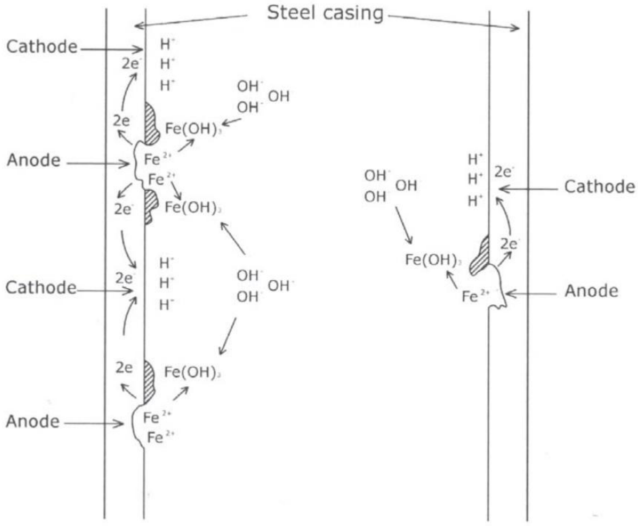

Figure 2.2: Spatial distribution of total dissolved solids (TDS) in the main aquifer of the study area, illustrating hydrochemical variability and zones of higher salinity.

2.2 Data Sources

The design presented is based on groundwater inventory, chemical and microbiological analyses, and hydrogeological interpretation reported in the PhD thesis; on review and environmental assessment of advanced wastewater treatment technologies including sand filtration, ozonation, membrane bioreactors, UV and advanced oxidation; and on standard design criteria for municipal wastewater treatment plants as reported in the international literature. Because continuous flow measurements and sewer monitoring are not yet available, flows and loads are determined from population projections and typical per capita wastewater generation.

2.3 Design Assumptions

Design assumptions including:
- Design population, horizon year: 450,000 inhabitants.
- Fraction of population connected at horizon year: 90%.
- Per capita wastewater production: 150 L/person·d.
- Average daily flow Qavg ≈ 60,000 m3/d.
- Maximum daily flow Qmax,d ≈ 78,000 m3/d.
- Peak hourly flow Qpeak,h ≈ 6,250 m3/h.

- Influent concentrations: BOD5 = 250 mg/L; COD = 500 mg/L; TSS = 250 mg/L; TN = 40 mg/L; TP = 8 mg/L; faecal coliforms ≈ 107 CFU/100 mL.
- Target effluent quality: BOD5 < 20 mg/L; TSS < 20 mg/L; TN ⩽ 15 mg/L; TP ⩽ 2 - 3 mg/L; faecal coliforms < 200 CFU/100 mL.

Table 2.1: Design flows and influent loads

Parameter	Value	Unit
Design population (horizon year)	450,000	persons
Connected fraction	90	%
Per capita wastewater production	150	L/person·d
Average daily flow Qavg	60,000	m3/d
Maximum daily flow Qmax,d	78,000	m3/d
Peak hourly flow Qpeak,h	6,250	m3/h
BOD5 concentration	250	mg/L
COD concentration	500	mg/L
TSS concentration	250	mg/L
TN concentration	40	mg/L
TP concentration	8	mg/L

2.4 Process selection

The PhD thesis evaluated several advanced treatment technologies—rapid sand filtration, membrane bioreactors (MBR) and ozonation—using life-cycle assessment. The analysis showed that sand filtration has induced environmental impacts that are lower than the prevented impacts, while MBR and ozonation show higher induced impacts due to their high energy consumption. Considering energy costs and maintenance requirements, this paper adopts the following configuration for West Omdurman:

- Preliminary treatment: coarse and fine bar screens, aerated grit chambers.
- Primary treatment: circular primary clarifiers.
- Secondary treatment: conventional activated sludge with nitrification–denitrification.
- Secondary clarification: circular secondary clarifiers.
- Tertiary treatment: rapid gravity sand filters.
- Disinfection: UV disinfection in a baffled contact tank.
- Sludge line: thickening, stabilization and dewatering, with controlled reuse/disposal.

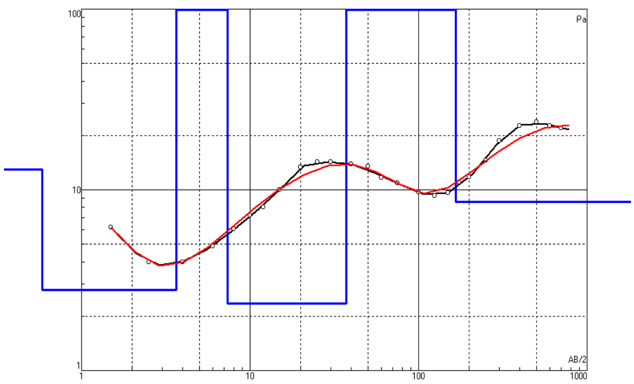

Figure 2.3: Process flow diagram of the proposed advanced wastewater treatment plant, showing inlet works, primary clarifiers, aeration basins with internal recycle, secondary clarifiers with return and waste activated sludge lines, rapid sand filters, UV disinfection channel and sludge treatment units.

Table 2.2: Summary of main process units and dimensions

Unit	Design basis	Number	Main dimensions (approximate)
Coarse & fine screens	Qpeak,h ≈ 6,250 m3/h, v ≈ 0.8 m/s	2 channels	Clear width ≈ 1 m per channel
Aerated grit chambers	30–45 s at Qpeak,h	2	Volume ≈ 35–40 m3 each
Primary clarifiers	SOR = 30 m3/m2·d at Qavg	2	D ≈ 36 m, water depth ≈ 3 m
Aeration basins	HRT = 8 h at Qavg	4	55 m × 20 m × 4.5 m (≈ 5,000 m3 each)
Secondary clarifiers	SOR = 25 m3/m2·d at Qavg	4	D ≈ 28 m, depth ≈ 3.5 m
Rapid sand filters	HLR = 7 m3/m2·h at Qmax,d	6	10 m × 8 m filter boxes (80 m2 each)
UV contact tank	30 min at Qmax,d	1	60 m × 10 m × 3 m (≈ 1,800 m3)

2.5 Expected Treatment Performance

Typical removal efficiencies for well-operated plants with this configuration are used to estimate expected effluent quality. Table 3 summarizes the expected performance.

Table. 2.3: Expected treatment performance

Parameter	Influent	Expected effluent	Overall removal (%)
BOD5 (mg/L)	250	≤ 15–20	92–94
COD (mg/L)	500	≤ 60–80	84–88
TSS (mg/L)	250	≤ 15–20	92–94
TN (mg/L)	40	10–15	60–75
TP (mg/L)	8	2–3	60–75
Faecal coliforms (CFU/100 mL)	≈ 107	< 200	> 99.999

3. Results and Analysis

3.1 Treatment Performance and Standards

The expected effluent quality in Table 3 meets typical international guideline values for treated wastewater used in restricted irrigation and, for many crops, in unrestricted irrigation with appropriate management. It also provides sufficient protection for groundwater when effluent is applied through controlled irrigation rather than uncontrolled percolation.

3.2 Environmental Performance of Advanced Options

The life-cycle assessment in the PhD thesis compared sand filtration, membrane bioreactors (MBR) and ozonation. It showed that sand filtration has prevented ecotoxic impacts that exceed induced impacts, while MBR and ozonation show higher induced impacts because of electricity consumption and, for ozonation, ozone generation. Under Sudanese conditions, where electricity is both expensive and intermittently unavailable, the configuration adopted in this paper conventional biological treatment with sand filtration and UV disinfection appears more sustainable and realistic than MBR or ozonation for a large municipal plant.

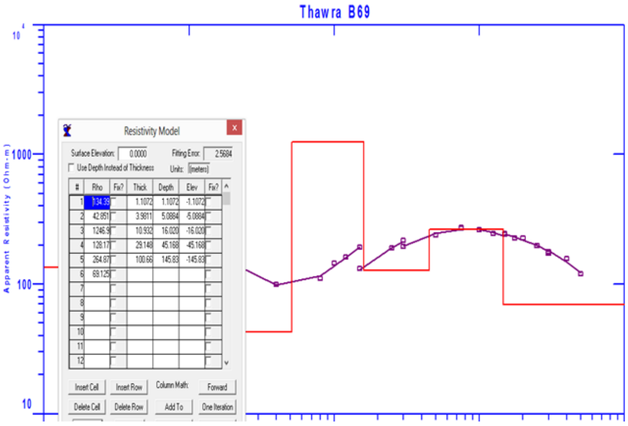

Figure 3.1: Induced and prevented potential environmental impacts from sand filtration, expressed as weighted and normalized impact potentials per cubic meter of treated effluent.

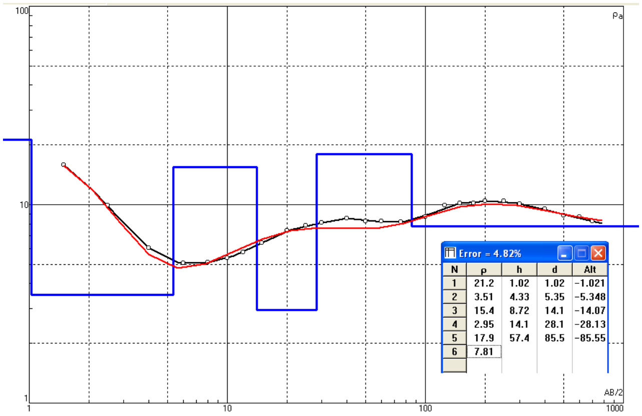

Figure 3.2: Induced and prevented potential environmental impacts from membrane bioreactor (MBR) treatment, including energy use for pumping, aeration and fouling control

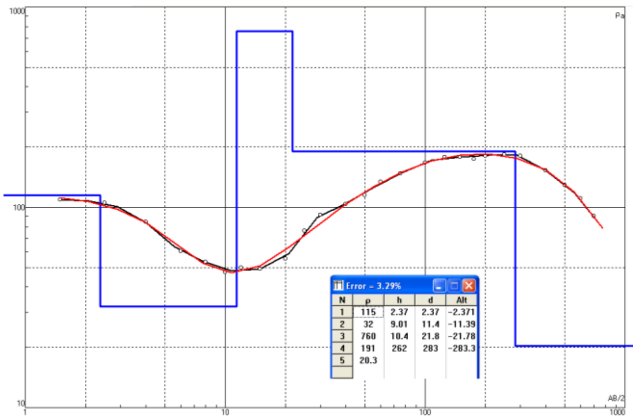

Figure 3.3: Induced and prevented potential environmental impacts from ozonation as an advanced treatment step, assuming an ozone dose of 8 mg O3/L

3.3 Implications for Groundwater Protection and Reuse

- Replacing thousands of scattered septic tanks and pits with a centralized WWTP and sewer network will substantially reduce direct infiltration of sewage into the Nubian and Quaternary aquifers. The contamination inventory showed that current practices have already led to nitrate, ammonia and microbiological contamination of wells used for public supply and irrigation. By intercepting wastewater, treating it to high standards and reusing it in controlled irrigation, the proposed WWTP will reduce nitrate leaching to aquifers, lower microbiological contamination of shallow groundwater and allow control of salinity and specific ions applied to the soil.

4. Conclusion and Recommendations

This paper has presented a complete conceptual design for an advanced wastewater treatment plant serving West Omdurman, Khartoum State, based on the hydrogeological context and contamination inventory of the area and on advanced technology assessments from the PhD thesis.

The main conclusions are:

- West Omdurman is experiencing serious groundwater quality degradation due to widespread use of on-site sanitation in unsuitable soils, coupled with intensive abstraction for domestic and agricultural use.
- A centralized WWTP with a design capacity of about 60,000 m3/d for a population of 450,000 inhabitants is required as a core component of a sustainable sanitation strategy.
- A process line consisting of conventional activated sludge with nitrification–denitrification, followed by rapid sand filtration and UV disinfection, offers a robust and sustainable solution for current conditions in Sudan, providing high effluent quality with moderate energy consumption.
- The proposed design yields realistic dimensions for all major units and is expected to achieve effluent concentrations suitable for agricultural reuse and protective of groundwater.
- Environmental assessment indicates that sand filtration has a more favourable balance between induced and prevented impacts than MBR and ozonation under local conditions, making it the preferred advanced treatment technology for the base case.

Recommendations for future work include:

- Detailed sewer network design and staged implementation to connect priority neighbourhoods and institutions.
- Pilot-scale demonstration of the selected treatment train under local conditions to verify design assumptions and refine operational parameters.
- Long-term monitoring of groundwater quality around the WWTP and irrigated reuse areas to quantify benefits for aquifer protection.
- Economic analysis and comparison of alternative configurations (including MBR or ozonation) under different electricity price and reliability scenarios.

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